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NOVEL FIRE TESTING METHODOLOGY: WHY, HOW AND WHAT NOW?

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ABSTRACT

In response to a need for rational, quantified, and repeatable assessment of building materials subject to heating during fire, a novel fire testing methodology, named the Heat-Transfer Rate Inducing System (H-TRIS), has been developed using an innovative thermal loading technique. H-TRIS is based on the use of a mobile array of propane-fired high performance radiant heating elements, along with a computer-controlled mechanical linear motion system. The thermal loading is actively controlled by incident heat flux measurements at the test element's exposed surface using a high precision loop feedback system. This paper presents the motivation behind the development of this unique testing methodology, the theoretical and practical procedures behind its conception and operation, and the potential value that H-TRIS may bring to the fire engineering design, research and certification communities.

KEYWORDS

H-TRIS, radiant heaters, thermal energy, heat flux, standard fire resistance test.

INTRODUCTION

Since the beginning of the 20th century the standard fire resistance test has been the predominant mean of characterizing the response of structural elements and materials in fires (Woolson, 1916; ISO 834, 1999; ASTM, E 119). In the late 19th century, a need to provide fire safety to buildings and cities had crossed the boundaries of engineering and became a social requirement in the rapidly growing building construction community (Gales et al., 2012). The adoption and extensive use of the 'standard' fire resistance test represented the response of the structural fire engineering community to overcoming the numerous inherent complexities in understanding the behaviour of real buildings in real fires. This was accomplished by basically rating (i.e. time to 'failure') simple building elements or isolated structural assemblies in standard fire resistance tests (i.e. furnace tests); and designers, product manufacturers and researchers were subsequently able to move forward without really addressing the fundamental science. The current system of fire rating building elements using furnace tests has been in existence since the turn of the last century (Hull and Ingberg, 1925) and remains (largely) unchanged since its initial development, despite enormous advances in fire safety science, thermo-mechanical response of construction materials, and structural fire modelling.

As noted by structural fire engineering researchers in the early 1970s; *"…it always must be borne in mind that in a strict sense standard fire endurance is not a measure of the actual performance of an element in fire, and, furthermore, that it is not even a perfect measure for comparison"* (Harmathy and Lie, 1970). For the following four decades the fire testing community made numerous attempts to modify and rationalize the rudimentary standard fire resistance test into what is now known as the 'modern' standard fire resistance test (Ödeen, 1970; Seigel, 1970; Babrauskas and Williams, 1978; Harmathy, 1981; Wickström, 1986; Sultan et al., 1986; Sterner and Wickström, 1989; Olsson, 1993; Wickström, 1994; Sultan, 2006). However, high operating costs, poor repeatability, unrealistic and/or inappropriate boundary conditions, and poor statistical confidence remain, to this day, common issues regarding the use of standard fire resistance tests for design, product development and rational, defensible scientific structural fire engineering research (Cooke, 1994; Beitel and Iwankiw, 2008 Law et al., 2011; Gales et al., 2012).

This paper presents a novel fire testing methodology, termed the Heat-Transfer Rate Inducing System (H-TRIS), which has been developed to address these and other issues; by fundamentally changing the method by which materials or assemblies are "heated".

REACTING TO A NEED – WHY?

The standard fire resistance was developed mainly to standardise a field in desperate need of regulation and material/product/design comparison and competition (i.e. fire ratings were needed). The fundamental problem is that in a furnace test the heat flux (i.e. thermal energy) absorbed by sample being tested is directly dependant on the gas phase temperature, as well on the characteristics and conditions of the furnace. Moreover, the thermal properties of the sample being tested highly govern the heat flux being absorbed by the sample (Harmathy, 1981; Welch and Rubini, 1997). Thus every sample absorbs a different heat flux, and hence a furnace cannot be used for the purposes of relative assessment of materials that have significantly different thermal properties (e.g. concrete, timber, steel). With time, the various players within the building construction industry have reacted and evolved in different ways as a reaction to the introduction of the standard fire resistance test.

Designers and Regulators

In the late 1920s, the young standard fire resistance test was widely recognized as a test that by no means represented reality (Ingberg, 1928). Researchers, most notably Simon Ingberg (1928), made extensive efforts to correlate a fire severity – using measurements from real burnout compartment tests – to the time-temperature curve of the standard fire resistance test using the 'Equal Area Concept'. Other researchers continued with the development of new concepts of equivalent fire severity based on other severity metrics; such as 'Maximum Temperature Concept', 'Minimum Load Capacity Concept', and 'Time-Equivalent' Formulae. Buildings could then be re-classified not just as a function of fuel load, and building elements which had 'equivalent' standard fire resistance times could be specified/required in designs. Today, structural fire engineering design still relies predominantly on the concepts of equivalent fire severity, and designs remain based on a considerable oversimplification of real fire (and structural) behaviour – unrealistic fires are used both for design and for comparative fire testing (i.e. fire rating).

While significant developments have occurred in fire dynamics and structural fire modelling in the past two decades, experimental science has lagged behind, in part due to a lack of understanding of the actual thermal loading experienced by materials in both real fires and standard fire resistance tests. Consequently, structural fire science's development in terms of materials' properties and structures' behaviour in fire stands on unstable ground, and using conventional testing techniques a fair comparison or quantification of structural response to fire is essentially impossible.

Product Manufacturers

Construction materials and products form the basis for the design of modern buildings. In today's building construction environment, in which designs are highly driven by optimization and costs, product manufacturers are constantly seeking a competitive advantage. The standard fire resistance test has allowed the various manufacturers and industries (i.e. concrete, timber, steel) to rate and, therefore compare, their products based on results from the tests, creating a field in which products are developed not necessarily to perform in real fires, but rather to perform in the standard fire resistance test, without deeply questioning their performance in real fire conditions.

The natural question that arises from this situation is then: Why is change needed? Can we, the structural fire engineering community, make things better? What might "better" look like and how can this be implemented? Could improvements reduce costs, increase sustainability, benefit speed and ease of construction, increase lifetime, or even make buildings safer? It is the engineers' role to address the almost infinite number of competing design goals presented by the performance world we live in, mostly by grouping things, categorising, and boxing knowledge into entities we can comprehend (Abecassis, 2010). But this has not been done without a cost; as pioneering fire engineers Law and Beever stated with respect to prescriptive design for fire, *"…even if all projects comply with codes, they are not all equally safe"* (Law and Beever, 1994), a quote that might well be extrapolated to most other communities within the building construction industry.

Researchers

Structural fire engineering researchers have for many decades made widespread use of the standard fire resistance test's time-temperature exposure curve without truly understanding the thermal loading to which materials are subjected in a real fire. This is hardly surprising since most structural engineers learn very little about heat transfer or fire dynamics, and therefore naively assume that the 'standard' fire really does describe an actual fire in a real building. As a result, material properties (thermal and thermo-mechanical) as well as full structural behaviour in fire have historically been defined almost entirely based on standard fire resistance testing of isolated structural elements in furnaces. Even modern research (e.g. Jeanes, 1982; Mostafaei, 2011; Stadler et al., 2011; Vassart and Zhao, 2011) continues to use furnace testing a means to attempt to understand structural response to fire, despite the poor repeatability and quantification available from furnace testing.

The high costs of large scale furnace testing are most times the limiting factor for many structural fire engineering research groups around the world. Thus, is common to observe that researchers try to get the most possible information out of a single standard fire resistance test by testing multiple systems in a single test and over-instrumenting the specimens to get the most out of it – while largely ignoring a detailed characterization of the thermal environment to which the elements are exposed. Furthermore, high costs force research programs to perform only a very limited number of standard fire resistance tests, and hence very little statistical analysis, which is badly needed to enable a reliability-based approach to design such as is used in other fields, is possible. Repeatability and the ability to quantify the thermal loading to which materials are exposed in a standard fire resistance test thus remains a serious and legitimate concern within the fire research community (Ödeen, 1970; Law, 1981).

HARMATHY AND LIE'S VIEW

Harmathy and Lie (1970), two of the most prominent fire scientists of the modern era, presented the current state of fire engineering in the 1970s, and predicted what they thought the future held for the standard fire resistance test:.

> *"To achieve maximum economy in fire endurance design, the fire load concept must be abandoned; the fire test must become a truer representation of the conditions that probably will be met under particular circumstances. This will mean, on the one hand,* ***the replacement of the standard temperature-time curve by more realistic ones or by a heat-flux-time relation*** *particular to the predominant window areas, window heights, etc., and, on the other hand, an increased emphasis on the end or boundary conditions in particular cases. This latter* ***information can be derived only from a thorough theoretical examination of the whole building****.*
>
> *An overall look at the building may reveal much more than the possible boundary condition for the individual elements. It may be found that the failure of a building will originate with an element not even exposed to fire, for example, collapse of a building may originate in an unexposed column that grows eccentric because of thermal expansion due to fire in an adjoining beam.*
>
> *Abandoning the standard temperature-time curve in favor of a realistic heat flux-time relation may seem a rather revolutionary change in the field of fire endurance testing. In the computer simulation of fires, however, this will simply mean the replacement of one set of boundary conditions by another set. It must be realized that the computer design for fire endurance is already a reality in a number of areas, which will continue to grow at approximately the same rate as the knowledge concerning thermal and rheological behavior of building materials at elevated temperatures increases.* ***Even the most sophisticated treatise on the behavior of buildings or building elements in fire remains mere speculation if it is not based on a thorough knowledge of the behavior of the component materials****. This is why the authors believe that any progress over the next 10 or 20 years will be measured by progress in understanding the behavior of materials."*

Unfortunately, some four decades after these statements were made relatively little has changed in the formal fire testing and fire endurance rating of structural materials, elements, and assemblies in fire.

NEW TEST METHODOLOGY – HOW?

Following Harmathy and Lie's (1970) lead, the new test method, or Heat-Transfer Rate Inducing System (H-TRIS), is based on the use of a mobile array of propane-fired high performance radiant heaters, along with a mechanical linear motion system (Figure 1). The thermal loading is *actively* controlled using incident heat flux

(HF) measurements taken from two water cooled Schmidt-Boelter heat flux sensors. These are placed at specimen's exposed surface, and using a high precision loop feedback system the linear motion system is computer-controlled in real time to adjust the heaters' location to follow any pre-defined time-heat flux relationship (as suggested in 1970 by Harmathy and Lie). H-TRIS allows an accurate *quantification* of the thermal *energy* absorbed by a tested element with high precision and repeatability; all at negligible economical and temporal costs in comparison to a standard furnace test.

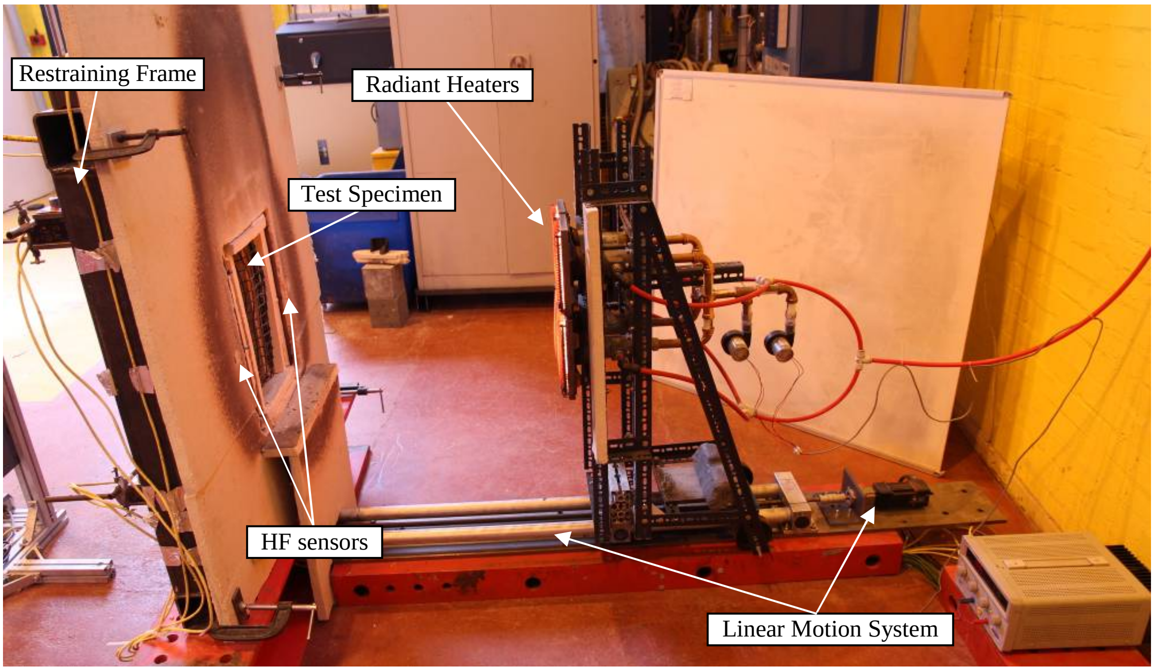

Figure 1: Heat-Transfer Rate Inducing System (H-TRIS).

Inverse Thermal Model

By controlling the distance between the radiant heaters and the specimen's exposed surface, H-TRIS is capable of reproducing any possible time versus absorbed heat flux curve (subject to the maximum incident heat flux that it can apply, which is in the range of 100 kW/m^2). Thus, tests may be conducted to reproduce a quantified absorbed thermal energy, or absorbed heat flux, equal to that experienced by materials or specimens in a standard fire resistance test in any specific testing furnace. For reproducing the thermal energy absorbed by specimens in a standard fire resistance test, a numerical inverse heat transfer model was developed based on through-thickness temperature measurements obtained during large-scale standard fire resistance experiments on concrete elements in the large scale standard floor testing furnace at EMPA, Switzerland (Terrasi et al., 2012). The inverse model calculates the thermal energy absorbed by specimens tested in a standard fire resistance test, by using experimental temperature readings as input to the model and calculating the necessary absorbed heat flux (i.e. the time-history of absorbed thermal energy) that generates the observed thermal gradients. A more detailed description of the inverse thermal model is avoided here but will be published elsewhere.

Once elucidated, the inverse model was subsequently coupled to a heat transfer model of H-TRIS' thermal conditions (i.e. radiative and convective losses at the specimen's surfaces) so as to compute the variation of incident heat flux with time to be applied by H-TRIS to reproduce 'furnace conditions' in terms of absorbed heat flux by the test specimen; as described by Eq. 1. A typical example of the inverse model's result is given in Figure 2, which shows the heat flux, $\dot{q}''_{obj,\,abs}(t)$, absorbed by the specimen in a standard fire resistance test along with the incident heat flux, $\dot{q}''_{obj,\,inc}(t)$, that must be applied by H-TRIS to reproduce the desired absorbed heat flux. Figure 2 illustrates the initial increase and subsequent stabilization of the absorbed heat flux in specimens tested in a standard fire resistance test; this has also been reported previously by other researchers (e.g. Sultan, 1996). Figure 2 shows the significant growth of the required incident heat flux at later stages of the test, when the losses by radiation and convection increase at the specimen's exposed surface. This is shown in

Eq. 1, where losses by radiation, $\dot{q}''_{rad}(t)$, and convection, $\dot{q}''_{conv}(t)$, have been estimated for the purposes of the current research using relatively crude empirical correlations (Incropera, 2002). Validation studies are described briefly below.

$$\dot{q}''_{obj,\,inc}(t) \;=\; \dot{q}''_{obj,\,abs}(t) \;+\; \dot{q}''_{rad}(t) \;+\; \dot{q}''_{conv}(t) \tag{1}$$

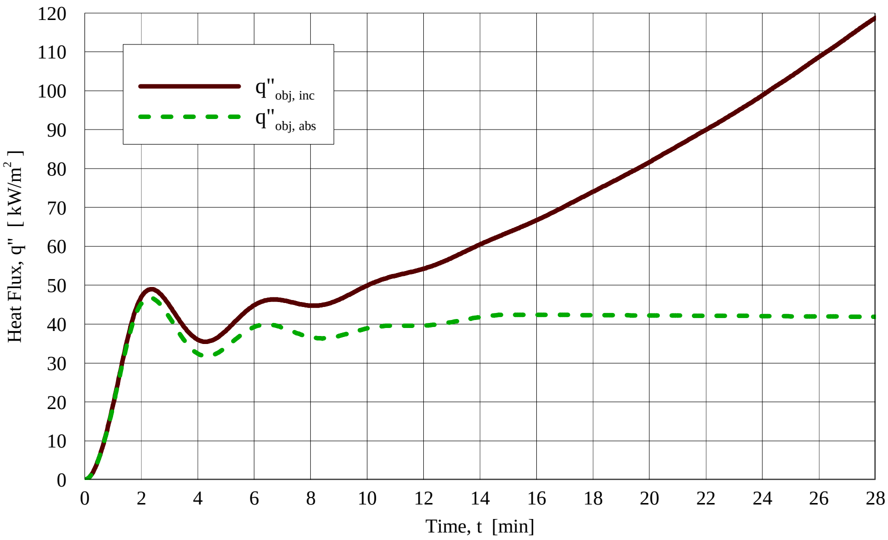

Figure 2: Objective time-heat flux curve, $\dot{q}''_{obj,\,inc}(t)$ and $\dot{q}''_{obj,\,abs}(t)$.

Thermal Exposure

The most significant improvement provided by this new testing methodology is the way in which specimens are heated. In a standard fire resistance test in a furnace, very powerful burners (gas or oil fuelled) are used to blow hot gases inside a regular prism shaped furnace. When testing walls or floors, one of the furnaces major boundaries is totally or partially replaced by the specimen being tested. The furnace itself becomes a heat transfer system, creating fundamental differences in how standard and repeatable the thermal energy absorbed by specimen being tested really is.

This was openly discussed during the 1970s and 1980s (Ödeen, 1970; Seigel, 1970; Babrauskas and Williams, 1978; Harmathy, 1981, Wickström, 1986; Sultan et al., 1986), and as a response to this, the plate thermometer made its way into the fire testing community in an attempt to homogenise the thermal loading of the majority of furnaces across Europe (which were recognized as not imposing the same thermal environment across the industry). In the early 1980s work begun to introduce the plate thermometer into the European version of the standard fire resistance test (Wickström, 1986; Wickström, 1994), successfully tackling many of the issues identified in the past.

The new testing device, H-TRIS, employs a new generation of radiant heaters (Figure 3) and exposes specimens to a pre-defined time-incident heat flux curve. Presently H-TRIS is capable of exposing a surface area of about 200mm × 400mm to heat fluxes between 5 and 100 kW/m^2, with homogeneity better than 90% across the specimen's exposed surface. The implementation of larger exposed surfaces and higher thermal loads is being considered, utilising an array of radiant heaters assembled in parallel.

The total thermal energy absorbed by the specimen during a test can then be estimated based on the following equation:

$$E_{abs} = \int_0^{t_i^*} \dot{q}''_{obj,\,abs}(t)\;\partial t \tag{2}$$

Where E_{abs} is the total thermal energy absorbed per surface area, $\dot{q}''_{obj,abs}(t)$ is the absorbed heat flux per surface area, and t_i^* is the duration of the test.

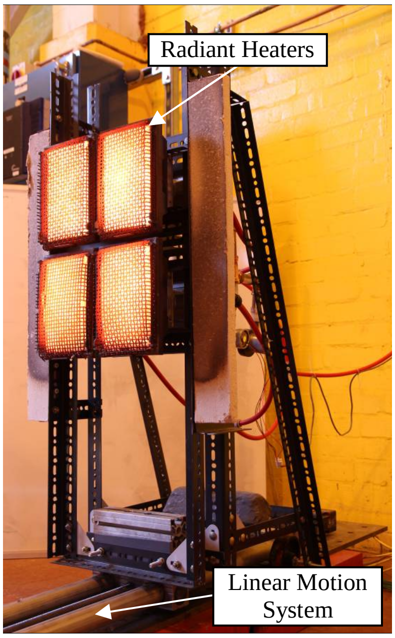

Figure 3: High performance radiant heaters.

Linear Motion System

H-TRIS' linear motion system was designed based on the use of an electronic rotary stepper motor in combination with a mechanical linear guidance system. Using these components the system is able to control the distance between the specimen's exposed surface and the radiant heaters with 0.1 mm precision. This high precision is essential to correctly expose test specimens to the high heat fluxes required to simulate furnace testing, particularly during the later stages of exposure. Based on a pre-test automatic calibration run, in which the radiant heaters location is systematically varied, heat flux readings at the specimen's exposed surface are taken in real time. Thus generating an incident heat flux versus distance between the radiant heaters and the specimen's exposed surface, $\dot{q}''_{calib,\,inc}(x)$ (see Figure 4). During a test, the automatic loop feedback system controls the position of the radiant heaters relative to the specimen's exposed surface at a pre-defined time step, Δt, and based on Eqs. 3, 4, and 5.

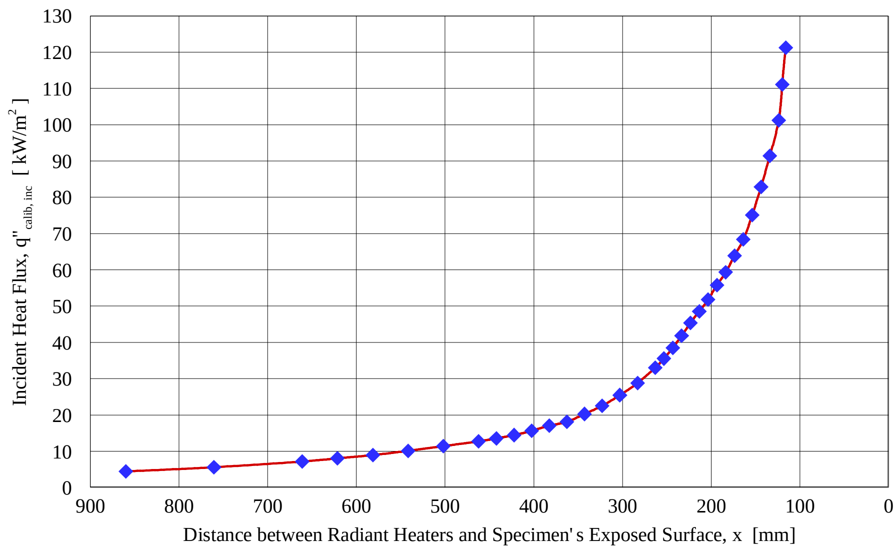

Figure 4: Calibration run, measured incident heat flux, $\dot{q}''_{calib,\,inc}$, versus distance between the radiant heaters and the specimen's exposed surface, x.

The velocity, $v(t_i)$, at which the radiant heaters displace between time steps (i) and (i+1), is calculated based on a 1st order finite difference approximation of the predefined objective time versus incident heat flux curve's time derivative, $\dot{q}''_{obj,\,inc}(t_i)$, (Figure 2) and the calibration distance versus incident heat flux curve, $\dot{q}''_{calib,\,inc}(x)$, from Figure 4, by means of Eq. 3:

$$v(t_i) = \frac{\dfrac{\Delta\, \dot{q}''_{obj,\,inc}}{\Delta\, t}(t)}{\dfrac{\partial\, \dot{q}''_{calib,\,inc}}{\partial\, x}(x)} = \frac{\dot{q}''_{obj,\,inc}(t_{i+1}) - \dot{q}''_{obj,\,inc}(t_i)}{\Delta\, t} \cdot \left(\frac{\partial\, \dot{q}''_{calib,\,inc}}{\partial\, x}(x) \right)^{-1} \tag{3}$$

To improve the incident heat flux repeatability between tests, the velocity of the radiant heaters at any given time, $(t_i = \Delta t \cdot i)$, is corrected based on live incident heat flux readings, $\dot{q}''_{H-TRIS,\,inc}(t_i)$, at the specimen's exposed surface:

$$v_+(t_i) = \frac{\dot{q}''_{obj,\,inc}(t_i) - \dot{q}''_{H-TRIS,\,inc}(t_i)}{\Delta t} \cdot \left(\frac{\partial\, \dot{q}''_{calib,\,inc}}{\partial\, x}(x) \right)^{-1} \tag{4}$$

Consequently, the position of the radiant heaters at the time step $(i+1)$ is calculated by the following equation:

$$x_{i+1} = x_i + \left(v(t_i) + v_+(t_i) \right) \cdot \Delta t \tag{5}$$

The above procedure is repeated during subsequent time steps such that the pre-defined intended time-history of heat flux is accurately followed, for each specific test and for the particular ambient conditions on the day of the test. Such a level of case-specificity and repeatability is simply not possible in a conventional furnace test operating on the basis of average gas phase temperature measurements.

Scaling Effect

The size of the tested specimens used in fire tests and tests of construction materials at elevated temperatures has always been a matter of discussion and debate within the structures in fire research community (Gales et al., 2012). An attempt to reproduce realistic boundary conditions on single or partial elements or assemblies being tested fundamentally conflicts with the objective of generating a standard, realistic, and reproducible test. The standard fire resistance test has been criticized for many decades for a number of reasons related to this issue (Law, 1981).

In its current configuration H-TRIS makes no attempt to test 'real' scale structural systems; however it does present great advantages in terms of standardisation and reproducibility of thermal loading. Along with H-TRIS, specimens can be placed into a custom designed mechanical loading frame capable of reproducing the mechanical stresses experienced by structural elements or assemblies in real buildings (see Figure 5). This is accomplished by using a hydraulic jack controlled by pump working on displacement or load control, and a custom designed support system able to replicate pinned-pinned, pinned-fixed or fixed-fixed mechanical boundary conditions. This is particularly important for testing materials such as high strength concrete, for which the presence of compressive load during heating is known to fundamentally alter its mechanical response and propensity for explosive spalling. Indeed, H-TRIS has been developed specifically to test large numbers of concrete samples to evaluate propensity for fire induced explosive spalling. More than 80 such tests have now been run at only a fraction of the cost of testing in standard fire resistance test, and with considerably superior repeatability and statistical confidence.

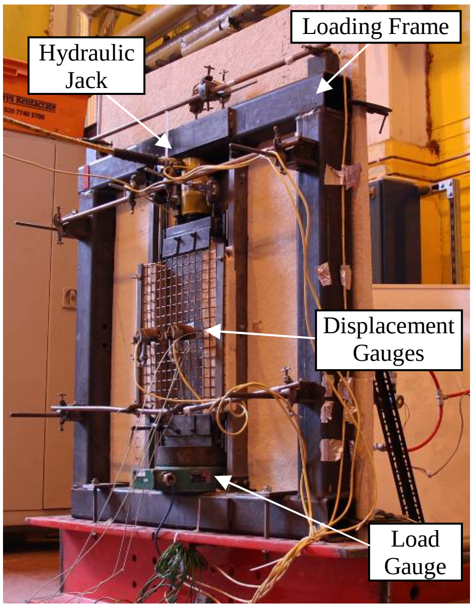

Figure 5: Custom design mechanical loading frame (back face view).

CORRELATION WITH ACTUAL FURNACE TESTS

To demonstrate the applicability of using H-TRIS to reproduce the thermal conditions (i.e. internal thermal gradients) experienced during a standard fire resistance test in a large scale floor testing furnace, a direct comparison was made between internal temperatures (at 10, 20 and 45 mm from the exposed surface) recorded inside high performance, 45 mm thick, concrete panels heated from one side using H-TRIS (configured to simulate the time history of heat flux expected for an ISO 834 fire in the floor furnace at EMPA), and those recorded during an actual furnace test of an effectively identical concrete element (i.e. same cross section, concrete mix, age, moisture condition, initial compressive stress, dimensions, etc) in the floor furnace at EMPA (Terrasi et al., 2012). The resulting comparison is shown in Figure 6, where it can be seen that H-TRIS imposes thermal gradients within the test specimens, similar to those imposed in the furnace tests; thus validating the use of this technique, particularly in studying behaviours which occur during the early stages of a fire, such as explosive cover spalling in concrete. Furthermore, Figure 6 illustrates the high repeatability of H-TRIS tests as compared with the scatter seen in the furnace tests, for a range of measured temperatures in identical specimens. Additional validation studies have been performed or are currently underway; these will be reported in detail elsewhere.

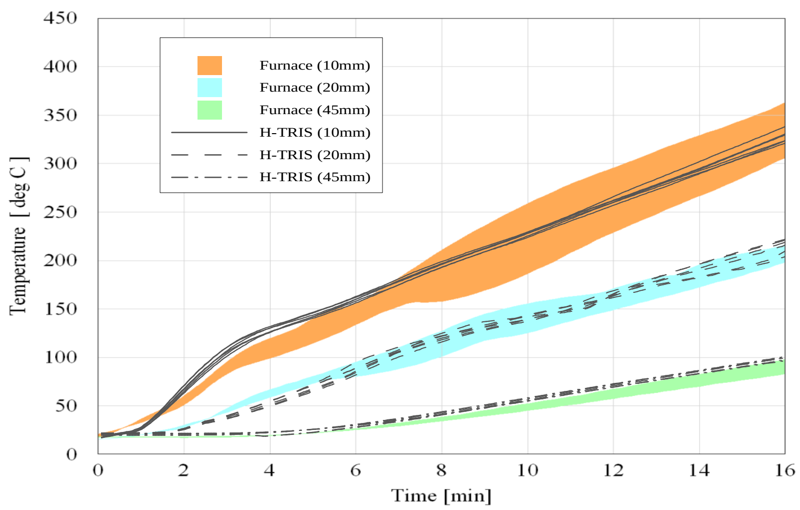

Figure 6: Comparison of concrete specimens' internal temperatures recorded in a furnace as compared against H-TRIS test results.

REACTION FROM THE WIDER COMMUNITY – WHAT NOW?

H-TRIS presents an opportunity for a more correct determination of materials' properties subject to severe heating and a more complete understanding of thermal phenomena which depend on the thermal loading (e.g. fire induced concrete spalling, intumescent fire protection systems' behaviour, etc). Structural and non-structural materials can now be tested at a negligible economical and temporal cost relative to large scale standard fire resistance testing. Thus, for the first time at this scale the quantification of the thermal energy absorbed, with high precision and defensible repeatability can be known with confidence. Consequently, the new testing approach is generating considerable interest from varied sectors within the building construction industry.

Product manufacturers

Manufacturers from all extremes of the construction industry have shown an interest in H-TRIS. The low costs, ease of testing and high repeatability are very attractive for an industry testing their products in expensive standard fire resistance tests. Some have even seen an opportunity in H-TRIS to develop and optimize their product at a low economical and temporal cost, but unfortunately still always with the clear ultimate objective of developing a product that will satisfactorily pass the standard fire resistance test in a certified fire testing laboratory. It's the authors' hope that with time, product manufacturers may shift their development processes into a development driven by performance of the product in real conditions, with H-TRIS being the tool that will allow them to make this transition; of course this will come with a change in the wider community (i.e. designers, regulators, and researchers).

Designers and Regulators

In today's building design environment engineers still make widespread use of Ingberg's (1928) Equal Area Concept to correlate 'real' fire scenarios to the 'standard' fire resistance test. Even though this concept presents a tool which allows designers to use rated systems in non-prescribed environments, it does present serious questions on the physical validity of the fire severity assessed through the Equal Area Concept. While the area under the curve in a time-temperature curve has no physical meaning, in a time-heat flux curve, as the one reproduced and controlled by H-TRIS), the amount of energy absorbed by the material con be quantified with high precision, allowing the correlation between energy absorbed and material properties. Since "temperature" is such a familiar concept to engineers and the general public alike, it is easy to forget that materials heat up due to a gradient of temperatures (i.e. energy exchange) rather than by single temperatures. Thus, it is heat flux which matters, not temperature *per se*.

Researchers

The low cost and high repeatability achieved by H-TRIS is without doubt what fellow researchers have seen as its most significant potential value, since it will allow them to break free from the economical constraints of the standard fire resistance test for many types of testing. It is particularly valuable in addressing Harmathy and Lie's (1970) concern that *"…even the most sophisticated treatise on the behavior of buildings or building elements in fire remains mere speculation if it is not based on a thorough knowledge of the behavior of the component materials."*

The ability to quantify the amount of energy absorbed by the materials tested is also a parameter that allows an improvement of the current analytical and numerical modelling validation. For example, when modelling the heat transfer into a test specimen in a standard fire resistance test in Europe, adiabatic surface temperature, which assumes that both convection and radiation thermal incidence are coupled into a single temperature, is used to set the boundary condition of the exposed surface (Wickström, 1994 and Wickström et al., 2007). To the authors' knowledge, this fundamental assumption has not been extensively discussed and validated within the fire testing nor fire research communities, and it is our hope that the development of tools like H-TRIS will stimulate a discussion and the better understanding of materials' thermal properties and boundary conditions at elevated temperatures.

CONCLUSIONS

As the fire engineering community drives towards the acceptance and implementation of performance based designs, it is fundamentally practically incorrect to depend entirely on conventional fire testing and rating (or equivalent) of structural and non-structural systems as the motivation for product manufacturers, designers, regulators and researchers. For the reasons found earlier, the standard fire resistance test cannot be the tool that will allow the further development of a profession in search for performance based design tools.

Experimental tools able to conduct studies with high repeatability, realistic boundary conditions, and high statistical confidence, all at low economical and temporal cost, will allow product manufacturers to develop products to perform in real conditions, allow designers and regulators to produce and approve systems with an understanding of the real levels of safety, and allow researchers to correctly define materials' properties and systems' behaviour in real, credible worst-case fire conditions. H-TRIS is nothing more than a tool that attempts to fill these needs in a manner which is explicitly based on absorbed heat flux (i.e. thermal energy absorbed by materials) and which treats all materials and systems equally for the same presumed fire conditions.

The development and validation studies described in this brief paper have shown that H-TRIS is capable of satisfactory reproducing the thermal conditions experienced within a test specimen that would be observed during a standard furnace test. Furthermore, it is able to reproduce these conditions rationally, quickly, repeatably, and at a fraction of the cost of large scale furnace testing.

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